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6. AUTHOR(S)

David Wineland

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
NIST, Div. 847
325 Broadway
Boulder, CO 80303

8. PERFORMING ORGANIZATION REPORT NUMBER none

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13. ABSTRACT (Maximum 200 words)

We investigate, theoretically and experimentally, methods to generate quantum mechanically entangled states of ensembles of atomic particles. The theoretical goals are: determine the best entangled states for particular applications and devise ways to generate these states and ways to measure them. The experimental goals are: demonstrate the increase in signal-to-noise ratio in spectroscopy using entangled particles, and find effective means to create the desired entangled states for particular measurements.

We have created entangled states of two and four trapped $^9Be^+$ ions in a single-step, deterministic way. These states are those desired for spectroscopy with higher signal-to-noise ratio than possible with unentangled atoms. The procedure can be scaled to large numbers of ions. We have identified causes of imperfect fidelity and are taking actions to eliminate these causes.

14. SUBJECT TERMS
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QUANTUM MEASUREMENT WITH ENTANGLED ATOMS

Final Report

David J. Wineland
National Institute of Standards and Technology

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A. STATEMENT OF THE PROBLEM STUDIED

We investigate, theoretically and experimentally, methods to generate quantum mechanically entangled states of atomic particles. The theoretical goals are: determine the best entangled states for particular applications and devise ways to generate these states and ways to measure them. The experimental goals are: demonstrate the increase in signal-to-noise ratio in spectroscopy using correlated particles, and find effective means to create the desired entangled states for other applications.

Specific goals:

Theoretical - address four questions: (1) what, in principle, are the best correlated states for a particular application and (2) what are the generators, or interaction Hamiltonians, which, in practice, can produce the desired states, (3) what is the best measurement strategy to use on the correlated states, and (4) what are the fundamental and practical applications in addition to those that have already been identified (e.g., spectroscopy and interferometry).

Experimental - (1) demonstrate the increase in signal-to-noise ratio in spectroscopy experiments using entangled particles, and (2) apply stimulated Raman transitions for generation of the entangled states.

B. SUMMARY OF THE MOST IMPORTANT RESULTS

B.1 Demonstrations of multi-particle entanglement

We have demonstrated entanglement of two and four trapped $^9Be^+$ ions [1]. The states we created have the form

where $*\downarrow\rangle_i$ and $*\uparrow\rangle_i$ denote two hyperfine ground states of $^9Be^+$ for the ith ion. These states were created from the state $*\downarrow\rangle_1 *\downarrow\rangle_2 **** \downarrow\rangle_N$ using a one-step process proposed by Mølmer and Sørensen [2]. Although the fidelity of the states is not perfect, it is high enough to prove entanglement unambigously, the first time this has been done for four particles. The fidelity of these states was limited by ion heating [3] and laser intensity fluctuations; problems we are working to correct.

B.2 Ion-trap development.

We desire to make the ion traps small because the motional oscillation frequencies, and therefore the speed of operations, increases proportionally to d^{-2}, where d is a measurement of the characteristic dimension of the trap. We have refined the techniques for constructing miniaturized ion traps, and have been using a trap based on electrodes which are lithographically plated onto laser-machined alumina substrates [3]. This involved four basic steps:

(1) Micromachining of the alumina substrates. Laser machined alumina substrates form the basic trap structure. We then use a phosphoric acid etch to further improve the smoothness of the machined edges.

(2) Substrate metallization. We first use a screen printing and high temperature firing technique to apply thick film Au contact pads for the wires leading from the trap. We then

developed a metal shadow mask that is a negative image of the circuit patterns on the substrates. We use this mask to apply a thin Ti adhesion layer (10 nm) and then a thicker Au layer (~ 800 nm) by electron beam evaporation.

(3) Surface mount bonding. We use gold wires which are attached to alumina substrates with thick film contact pads to bond the RC filter components to the substrates.

(4) Substrate bonding. After all components are spot welded to the substrates, we then bond two substrates together with a spacer. We have tried several "glues" for this purpose and have been limited by high-voltage surface breakdown across the glue in several instances. We are still addressing this problem of bonding, including trying the use of insulating screws to hold the trap together.

B.3 Study of limitations

We published an extensive paper which examines methods for, and practical limitations to, quantum state synthesis and quantum logic based on trapped atomic ions [4]. We have examined several possible decohering mechanisms and have attempted to identify the most important of these. Current experiments are limited by heating of the ion motion which we believe is caused by fluctuating patch potentials on the electrode surfaces [3]. Although we hope to be able to identify and eliminate the causes of these fluctuations, we are also pursuing methods of "sympathetic cooling" to overcome the effects of the heating [5].

More fundamentally, we believe that the fidelity of logic operations will be limited by the effects of the 3N-1 "extraneous" motional modes of N trapped ions. These effects include (1) off-resonant excitation of the extraneous modes, (2) cross-mode coupling, and (3) fluctuations in the rates of logic operations due to thermal excitation of these extraneous modes. Our main approach to this problem is to multiplex using small numbers of ions in traps which are interconnected in an array [4]. We are implementing the first version of this scheme by constructing a "dual" trap where these ideas can be tested.

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C. PUBLICATIONS:

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C(b). Papers published in nonpeer-reviewed journals or in conference proceedings:

1. "Entangled states of atomic ions for quantum metrology and computation," D.J Wineland, C. Monroe, D.M. Meekhof, B.E. King, and D. Leibfried, W.M. Itano, J.C. Bergquist, D. Berkeland, J.J. Bollinger, and J. Miller, in *Atomic Physics 15*, ed. by H.B. van Linden van den Heuvell, J.T.M. Walraven, and M.W. Reynolds, (Proc.15th Int. Conf. on Atomic Physics, Amsterdam) (World Scientific, Singapore, 1997) pp. 31-46.
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10. "Entanglement of Trapped Ions," C. Monroe, C. A. Sackett, D. Kielpinski, B. E. King, C. Langer, V. Meyer, C. Myatt, M. Rowe, Q. Turchette, W. M. Itano, D. J. Wineland, in *Atomic Physics 17* (Proc. 17th International Conference on Atomic Physics, Florence, 2000), to be published.

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1. "Experimental violation of Bell's inequalities with efficient detection," M. A. Rowe, D. Kielpinski, V. Meyer, C. A. Sackett, W. M. Itano, C. Monroe, and D. J. Wineland, *Nature*, submitted.
2. "A decoherence-free quantum memory using trapped ions," D. Kielpinski, V. Meyer, M. A. Rowe, C. A. Sackett, W. M. Itano, C. Monroe, and D. J. Wineland, submitted to *Science*.

D. SCIENTIFIC PERSONNEL

- Dr. Wayne Itano (staff member)
- Dr. Christopher Monroe (staff member)
- Dr. David Wineland (staff member)
- Brian King (graduate student, Univ. of Colorado, 1994-1999, received Ph.D. degree, 1999)
- David Kielpinski (graduate student, Univ. of Colorado, 1998 - present)
- Dr. Christopher Wood (postdoc, 1997-1998)
- Dr. Christopher Myatt (postdoc, 1998-2000)
- Dr. Quentin Turchette (postdoc, 1998-2000)
- Dr. Cass Sackett (postdoc, 1998-2000)
- Dr. Mary Rowe (postdoc, 1999 - present)
- Dr. Volker Meyer (postdoc, 1999 - present)